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Colloidal Silica: Cement Enhancing Admixture Product Evaluation

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Background

As Class F- fly ash (F-ash) becomes scarce, PCC engineers will look to other supplemental cementitious materials (SCM) to replace F-ash and its ASR mitigating properties. Colloidal silica (CS), or nano-silica, has been shown to mitigate ASR at certain replacement levels; however, CS cannot be a full replacement of F-ash. Engineers at the Nebraska Department of Transportation (NDOT) learned of CS from a presentation given by Intelligent Concrete, Inc. at the 2019 Nebraska Concrete Professionals Association Conference and decided to investigate the potential use of CS in NDOT concrete mix designs.

Purpose of the Investigation

This research investigated the potential to use colloidal silica as a cement enhancing admixture in NDOT's concrete mix designs. Engineers had two objectives in this study:

1. Determine if CS can enhance high, early strength for use in patching and repairs.
2. Determine if CS can maintain or improve ASR mitigation as F-ash content is decreased.

Laboratory Investigation (Test Methodology)

Standard Testing

NDOT researchers followed four Department of Transportation testing standards for cements used in construction and emergency repairs shown in Table 1.

Table 1 - Standard Test Methods Used in NDOT Colloidal Silica Testing

1. ASTM C109, *Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50mm] Cube Specimens)* [1]
2. ASTM C191, *Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle* [2]
3. ASTM C1567, *Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)* [3]
4. AASHTO T380, *Standard Method of Test for Potential Alkali Reactivity of Aggregates and Effectiveness of ASR Mitigation Measures (Miniature Concrete Prism Test, MCPT)* [4]

NDOT researchers obtained CS and developed four matrices of mix designs to test different CS addition or replacement levels. Two matrices were designed for C109 and C191 testing to determine if CS could be used in rapid repair projects. The other two matrices were designed for C1567 and T380 testing to determine if CS could provide additional ASR mitigation. PCC laboratory technicians prepared both blended samples (used as control) and CS test samples for all testing.

Materials

Engineers based the mix designs for testing CS on a Type IP inter-ground cement control sample and two Type I/II and F-ash blended cement control samples. Table 2 shows Control ID, Cement Type, CaO/SiO_2 ratios, and Tests Conducted. Engineers chose Control A & Control B based on ratios known by the Department to pass ASTM C1567. They chose Control C to test if CS could improve C1567 performance of cements with ratios that did not pass C1567. The colloidal silica product, Nouryon's Levasil CB25A, is a nano-silica and water colloid and had a silica concentration of 30.3%, was obtained from Nouryon. Water was introduced to mixes either as prime water (municipal water), or as a combination of prime water and CS water (colloid water content).

Table 2 - Control samples for Colloidal Silica Testing

CONTROL ID	CEMENT TYPE	CaO/SiO_2 *Ratio*	TESTS CONDUCTED
Control A	Type IP-25	*1.60*	C109 & C191
Control B	Type I/II w/ 22% F-ash	*1.81*	C1567 & T380
Control C	Type I/II w/ 20% F-ash	*1.89*	C1567 & T380

Admixture (Addition) vs. SCM (Replacement)

I. CS Admixture (Addition)

Colloidal silica can be treated as an admixture, where the percentage of CS mass added is based on the cementitious materials. In admixture (addition) calculations, the control interground or blended cement represents 100% of the sample mass. Matrix 1 and Matrix 2 percentage values for each sample sum to greater than 100% which represents the mass of CS added to the control cement. For example, C109-CS1 had 100% IP and added 1% of the IP mass via the CS admixture. The total weight of the sample was 101% that of Control A. The proportions of Type I/II and F-ash remain the same and accounts for all cementitious powder mass needed for any batch. The CS is added to the mix with the tail water.

II. CS SCM (Replacement)

Colloidal silica can also be treated as an SCM, where the CS mass replaces an equivalent mass of the cementitious powders. The total mass of the Type I/II and F-ash is reduced and replaced by CS. The total cementitious materials in a batch will be comprised of the Type I/II, F-ash, and CS and the mass of cementitious material will be identical across the control and experimental samples. Three options exist for reducing cementitious materials:

A. Type I/II and F-ash can be reduced proportionately. This option reduces the mass of cement batched but maintains the proportion of Type I/II and F-ash. In field implementation, this is how the CS would be batched, as the cement powder will be at a pre-set proportion provided by the manufacturer.

B. F-Ash can be replaced by colloidal silica. This option reduces the mass of F-ash and the mass of Type I/II remains constant for any given batch. This is easily achieved if the concrete is cast in a lab or at a cement blending plant. Manufacturer provided cement will be set at proportion higher Portland to F-ash ratio and adding the CS will effectively lower that ratio to the final mix design specifications.

C. Type I/II can be replaced by colloidal silica. This option would reduce the mass of Type I/II in the cement powder but is impractical, and so is not considered a useful option.

Researchers designed two matrices (Matrix 1 and Matrix 2) treating the colloidal silica as an admixture (I), and two matrices (Matrix 3 and Matrix 4) treating CS as an SCM (II) following Option B. Example calculations are provided later in this report.

Matrix 1: Strength Activity Index and Set Time Testing: Type IP Cement

I. CS Admixture (Addition)

Matrix 1 was designed as an admixture for a 1% mass addition of CS to Control A. Matrix 1 samples were tested following test standards C109[1] for strength activity index and C191[2] for set time. The C109 and C191 matrix is shown in Table 3. The CS admixture samples were labeled as C109-CS1 and C191-CS1 for each respective test.

Table 3 - Matrix 1: Strength Activity and Set Time Testing

Matrix 1 - C109 and C191 Admixture			
C109 Addition	Percentage %		
	IP		CS
Control A	100		0
C109 -CS1	100		1*
C191 Addition	Percentage %		
	IP		CS
Control A	100		0
C191 - CS1	100		1*
*The CS mass was 1% of the IP mass. The mass of C109-CS1 and C191-CS1 were 101% of the mass of Control A.			

C109 - Strength Activity Index

Research started with C109 testing. The research design called for testing nine, 2-in cubes for each cement sample for compressive strength after hydrating for 3, 7, and 28 days. The flow of the mortar was measured and the water in the mix was adjusted to meet the requirements of C109. Adding colloidal silica to the mix reduced workability and researchers determined the correct amount of water to add to CS samples to meet the flow requirement. Once the flow was met, the cubes were cast and cured in the moist room in the NDOT PCC laboratory.

C191 - Set Time Testing

Testing for set time was conducted following standard C191. The technician added water to the control cement until the Vicat needle penetrated the paste 10 mm, which occurred at adding 185.3 grams of total water. Researchers added the same mass of water to the sample with 1% CS-added cement paste. Researchers observed that adding CS to the mix increased the water demand and the first sample did not meet the penetration requirements. A second batch was mixed with 179 g prime water and 10.1 g CS water for a total of 189.1 g of water. This resulted in a valid paste sample and the set times were recorded.

The second and third matrices were designed for a 2% and 3% addition to Control B and Control C to determine if CS can maintain or improve ASR mitigation as F-ash content is decreased. The second and third matrices were tested following standards C1567[3] and T380[4].

Matrix 2: ASR Mitigation Testing

I. CS Admixture (Addition)

Matrix 2 treated CS as an admixture to a Type I/II and F-ash blended cement prepared for C1567 and T380 testing. Colloidal silica addition amounts were determined based on a 2%-wt. and 3%-wt. of the mass of cement required for each test. The goal of the addition testing was to determine if CS mitigated ASR as F-ash percentage was reduced and Type I/II cement percentage increased.

C1567 - Accelerated Mortar-Bar Method

The matrix for colloidal silica addition in C1567 testing is shown in Table 4. Two control cements were used in C1567 and T380 testing. Control B, a 78% Type I/II cement with 22% F-ash, had a ratio of *1.81* and produced passing C1567 results. Control C, which was an 80% Type I/II cement with 20% F-ash had a ratio of *1.89* and did not produce passing C1567 results. The samples with CS addition to Control B were identified as C1567-CS2-B *(1.85)* and C1567-CS3-B *(1.88)*. C1567-CS2-C *(1.94)* and C1567-CS3-C *(1.96)*.

Table 4 - Matrix 2: CS Admixture (Addition) in C1567 Control B and Control C

Matrix 2 - C1567 Control B				
C1567 Addition	Percentage %			CaO/SiO_2 Ratio
	I/II	F-ash	CS	
Control B	78	22	0	1.81
C1567-CS2-B	80	20	2	1.85
C1567-CS3-B	81	19	3	1.88
Matrix 2 - C1567 Control C				
C1567 Addition	Percentage %			CaO/SiO_2 Ratio
	I/II	F-ash	CS	
Control C	80	20	0	1.89
C1567-CS2-C	82	18	2	1.94
C1567-CS3-C	83	17	3	1.96
*The CS mass was 2 and 3% of the Type I/II and F-Ash mass. The experimental samples were 102% and 103% of the mass of Control B and Control C.				

T380 - Miniature Concrete Prism Tests for ASR Mitigation

T380 testing specimens used the same percentages of Type I/II and F-ash as the C1567 samples, however, the sample identifications changed to uniquely identify the sample to the T380 testing. The control samples were still identified as Control B, and Control C. The testing specimens were identified as T380-CS2-B, T380-CS3-B, T380-CS2-C, and T380-CS3-C. The T380 specimens are shown in Table 5.

Table 5 -Matrix 2: CS Admixture (Addition) in T380 Control B and Control C

Matrix 2 - T380 Control B				
T380 Addition	Percentage %			CaO/SiO_2 Ratio
	I/II	F-ash	CS	
Control B	78	22	0	1.81
T380-CS2-B	80	20	2	1.85
T380-CS3-B	81	19	3	1.88
Matrix 2 - T380 Control C				
T380 Addition	Percentage %			CaO/SiO_2 Ratio
	I/II	F-ash	CS	
Control C	80	20	0	1.89
T380-CS2-C	82	18	2	1.94
T380-CS3-C	83	17	3	1.96
*The CS mass was 2 and 3% of the Type I/II and F-Ash mass. The experimental samples were 102% and 103% of the mass of Control B and Control C.				

Matrix 3: ASR Mitigation Testing

II. CS SCM (Replacement)

C1567 - Accelerated Mortar-Bar Method and T380 - Miniature Concrete Prism Tests for ASR Mitigation

Matrix 3 treated CS as a replacement of F-ash content in a Type I/II and F-Ash blended cement prepared for C1567. This matrix was developed after the addition testing concluded. Colloidal silica replacement amounts were determined based on a 2%-wt. and 3%-wt. of the mass of cement required for the C1567. The goal of the replacement testing was to determine if CS mitigated ASR as F-ash content was reduced and supplemented by CS, while the Type I/II percentage remained unchanged.

The matrix for colloidal silica replacement in C1567 testing is shown in Table 6. The same control and SCM replacement percentages were also used in T380 testing. Control B, a 78% Type I/II cement with 22% F-ash, had a ratio of *1.81* and produced passing C1567 results. The samples with CS replacement of F-ash in Control B were identified as C1567-CS2R-B *(1.83)* and C1567-CS3R-B *(1.85)*. The T380 CS samples were identified as T380-CS2R-B and T380-CS3R-B.

Table 6 - Matrix 3: C1567 CS SCM Replacement Testing

Matrix 3				
C1567 Replacement	Percentage %			CaO/SiO_2 Ratio
	I/II	F-ash	CS	
Control B	78	22	0	1.81
C1567-CS2R-B	78	20	2	1.83
C1567-CS3R-B	78	19	3	1.85

Matrix 3
C1567 Replacement

In replacement calculations, the mass of the CS counted towards the "dry mass total" and replaced an equivalent mass of F-ash. As the F-ash was reduced, the CS replaced the mass of the ash, while the Type I/II cement mass remained constant. This resulted in an increase in the CaO/SiO2 ratio for each cement; however, the increases were less than in the CS addition mixes from Matrix 2.

Control B
C1567-CS2R-B
C1567-CS3R-B

Matrix 4: Strength Activity Index and Set Time Testing: Type I/II Cement and F-Ash

II. CS SCM (Replacement)

C109 - Strength Activity Index and C191 – Vicat Set Time Testing

After analyzing results from Matrices 1-3, the researchers decided to continue testing colloidal silica as a replacement during the summer of 2020. A matrix for C109 and C191 testing at 2% and 3% CS replacement was established and is shown in Table 7, respectively.

Table 7 - Matrix 4: C109 and C191 CS SCM Replacement Testing

Matrix 4 - C109 - II	Testing CS 2% and 3% replacement	
	Percentage %	
	Type I/II	CS
Control - IIA	100	0
C109 -IIA-CS2	98	2
C109 -IIA-CS3	97	3
Matrix 4 - C191 - II	Testing CS 2% and 3% replacement	
	Percentage %	
	Type I/II	CS
Control - IIB	100	0
C191 -IIB - CS2	98	2
C191 - IIB - CS3	97	3

An NDOT PCC technician cast Control IIA cubes using Type I/II cement for C109 testing which prescribes a water to cement ratio of 0.485. The flow was measured at 101. The flow for specimens with CS replacement was measured and the water content was adjusted until the flow was within ± 5 of the control. During this process, researchers discovered the water requirements varied greatly. C109-IIA-CS2 required no reduction of prime water due to the addition of CS water to meet the flow requirements which was measured at 106. Researchers reduced the prime water by 3% for C109-IIA-CS3, which had a measured flow of 102. All three sets of cubes were cured in the PCC laboratory moist room and broken at 3, 7, and 28 days.

During C191 follow-up testing, the technician prepared pucks to measure set time. The control sample was prepared, and the water requirement recorded once the initial drop met C191 requirements. The water was adjusted until the initial drop requirement was met. As observed in C109 testing, prime water requirements were reduced with CS in the mix. Set times were recorded when the drop for each sample met the C191 requirement.

Results

Matrix 1 – Strength Activity Index and Set Time Testing: Type IP Cement

I. CS Admixture (Addition)

ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. Cube Specimens)

Control A and CS sample C109-CS1 were cast into cubes sets. The cubes were broken after 3, 7, and 28 days of curing. Control A exhibited strengths of 3,170 psi at 3 days, 4,180 psi at 7 days, and 5,300 psi. Sample C109-CS1 exhibited strengths of 3,530 at 3 days, 3,860 psi at 7 days, and 5,620 psi at 28 days. Control A cubes and C109-CS1 cubes differed in strength by only about 6% at 28 days. No significant difference in compressive strength indicates that colloidal silica does not provide an advantage in strength gain over Type I/II cements used by NDOT. The results are shown in Figure 1.

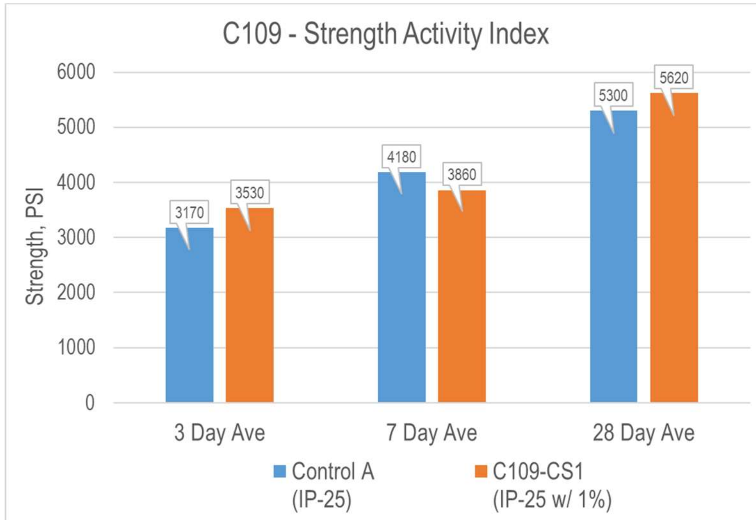

Figure 1 - Compressive strength of cubes with 1% CS replacement.

ASTM C191 Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle

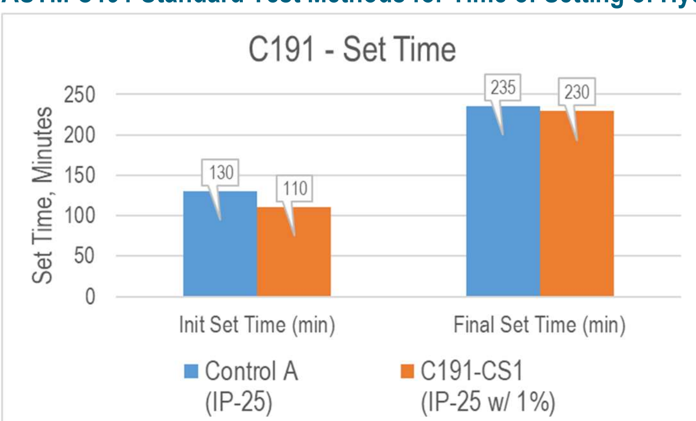

Figure 2 - CS showed a slightly faster initial set time in C191 testing.

The set time for Control A and CS sample C191-CS1 was measured using C191. Control A had an initial set time of 130 minutes and a final set time of 235 minutes. Sample C191-CS1 had an initial set time of 110 minutes and a final set time of 230 minutes. The initial set time for CS was approximately 20 minutes faster than the set time for Control A, while the final set time for CS191-CS1 was only 5 minutes earlier than Control A. The set times are compared in Figure 2. Results indicate that concrete with CS will set faster than Type IP, however contractors and maintenance crews will not observe a loss in workability or a drastic shortening of the placement window.

Matrix 2 – ASR Mitigation Testing

I. CS Admixture (Addition)

ASTM C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

All CS admixture samples based on Control B passed C1567 testing at 28 days. Control B expanded 0.11%. Colloidal silica sample C1567-CS2-B *(1.85)*, which increased Type I/II content to 80% and reduced F-ash to 20%, also expanded 0.11%. These samples are considered passing at the tolerance threshold of the test. Colloidal silica sample C1567-CS3-B *(1.88)*, comprised of 81% Type I/II cement and 19% F-ash, expanded the least of the three samples at 0.09%. The expansions are show in Figure 3.

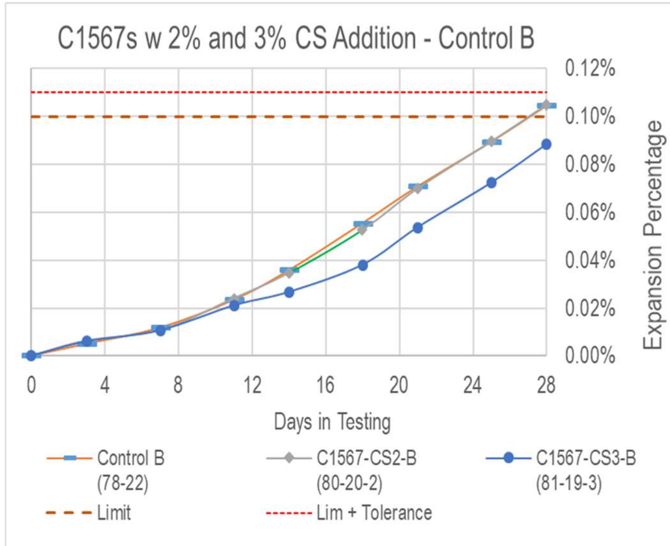

Figure 3 - Control B and CS Addition C1567 Expansions.

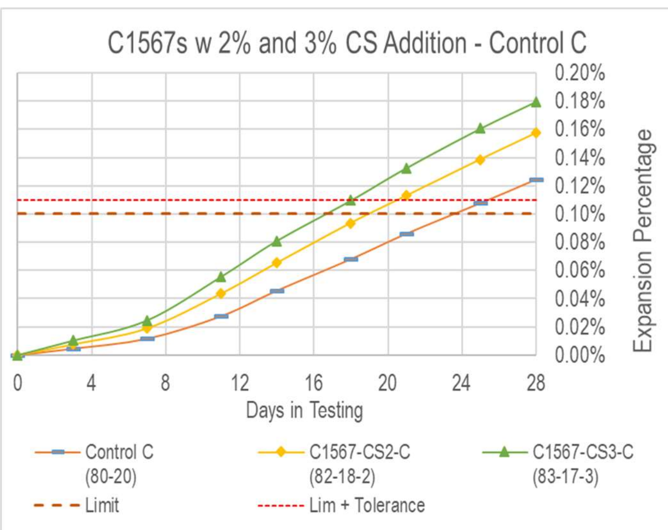

Figure 4 - C1567 Expansions of 80% Type I/II Mortar Bars with CS Additions

All CS admixture samples based on Control C failed C1567 testing at 28 days. Control C expanded 0.12% expansion. Colloidal silica sample C1567-CS2-C *(1.94)*, which increased Type I/II content to 82% reduced F-ash to 18%, expanded 0.16%. Colloidal silica sample C1567-CS3-C *(1.96)*, comprised of 83% Type I/II cement and 17% F-ash, expanded the most of the three samples at 0.18%. The expansions are shown in Figure 4.

Comparing the two groups of colloidal silica addition samples reveals that supplementing blends with F-ash percentages at 18% and below will not adequately mitigate ASR expansion. CS improves ASR mitigation at the 3% addition level in a blended cement comprised of 81% Type I/II and 19% F-ash blended cement. Addition of CS to the 78% Type I/II at the 3% level may allow NDOT to accept cements from manufacturers with a 19% F-ash content as F-ash becomes scarce.

AASHTO T380, Standard Method of Test for Potential Alkali Reactivity of Aggregates and Effectiveness of ASR Mitigation Measures (Miniature Concrete Prism Test, MCPT)

T380 considers samples with expansion less than 0.020% at 56-days of testing to be effective at mitigating ASR. All six samples expanded less than 0.020% at 56 days. Engineers directed the test be continued for 84 days, the maximum specified test duration. At 84 days, all but one sample exhibited less than 0.020% expansion.

Control B exhibited less expansion than the 2% and 3% additions. Control B (78% Type I/II cement) expanded the least at 0.012%, T380-CS2-B expanded 0.013%, and T380-CS3-B expanded the most at 0.015%. Expansion in the CS addition samples appeared to slow toward the end of testing indicating these samples will provide long-term durability. Expansions of the Control B samples are shown in Figure 5.

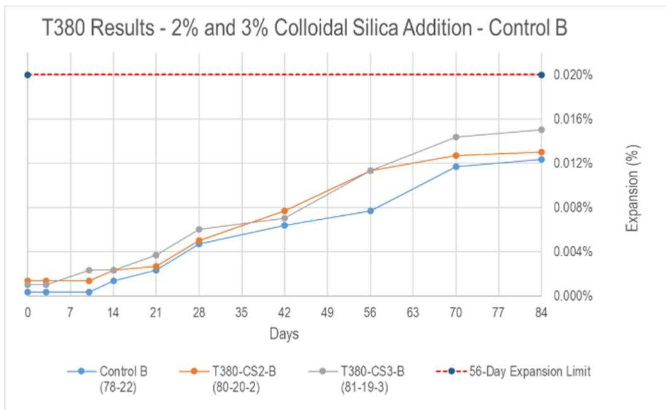

Figure 5 - T380 Expansions of Control B Mini-Prisms with Colloidal Silica Additions

Expectedly, Control C showed more expansion than the 3% addition of CS to the Control B sample group. The 2% and 3% additions to the Control C sample group both expanded more than Control C. Control C (80% Type I/II cement) expanded 0.017%, T380-CS2-C expanded 0.019%, and T380-CS3-C expanded the most at 0.021%, which exceeded the T380 expansion threshold. The expansion of the Control C samples appear to continue at a linear rate, suggesting this mix will have durability issues as time progresses. Expansions of the Control C samples are shown in Figure 6.

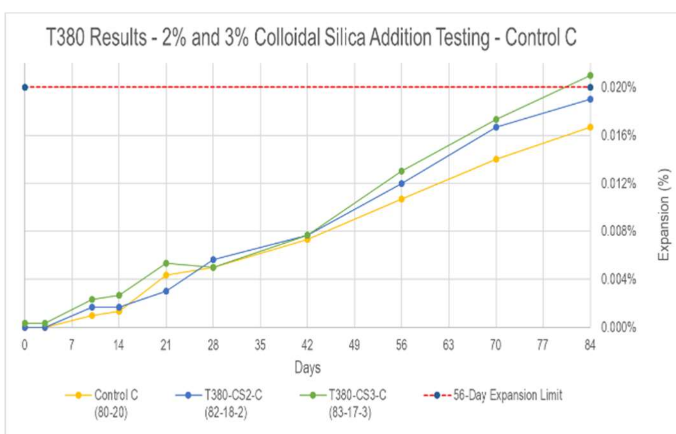

Figure 6 - T380 Expansions of Control C Mini-Prisms with Colloidal Silica Additions

Matrix 3 – ASR Mitigation Testing

II. CS SCM (Replacement)

ASTM C1567 Standard Test Method for Determining the Potential Alkali-Silica Reactivity of Combinations of Cementitious Materials and Aggregate (Accelerated Mortar-Bar Method)

Samples that treated CS as a replacement of F-ash content in a blended cement all passed C1567 testing. Control B *(1.81)* was used for replacement samples and it expanded 0.10%. C1567-CS2R-B *(1.83)* expanded 0.09%. C1567-CS3R-B *(1.85)* expanded 0.07%. This indicates that replacing F-ash with CS can improve ASR mitigation. The expansions of mortar bars with CS replacement are shown in Figure 7.

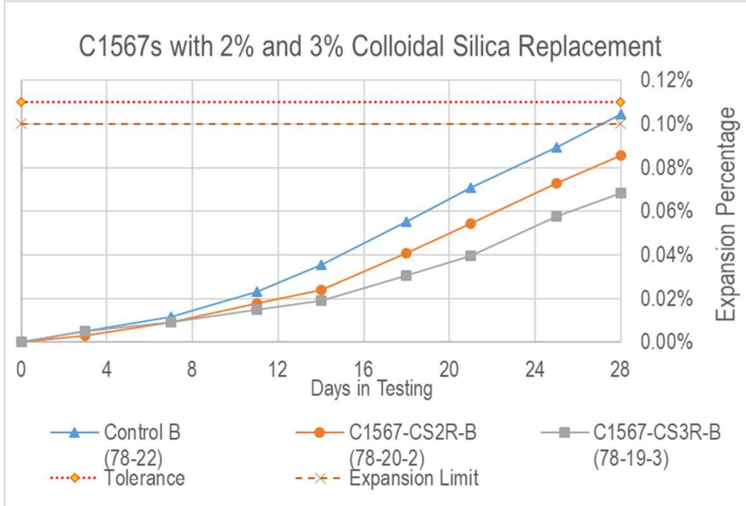

Figure 7 - Colloidal Silica samples that replaced F-ash in a blended cement reduced expansion in C1567 testing.

The improvements shown by lowering the F-ash percentage to 19% of a mix indicate that colloidal silica can be used to mitigate ASR in cements that have a low F-ash content. In order to achieve this composition in the field, the cement manufacturers will need to provide a cement that is approximately 80.4% Type I/II and 19.6% F-ash.

Matrix 4 – Strength Activity Index and Set Time: Type I/II Cement and F-Ash

II. CS SCM (Replacement)

ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. Cube Specimens)

The strength activity indexes of Control IIA, IIA – CS2, and IIA – CS3 cubes were measured at 3, 7, and 28 days. Control IIA exhibited strengths of 3886 PSI at 3 days, 4663 PSI at 7 days, and 4612 PSI at 28 days. The control samples appear to have achieved maximum strength by 7 days. IIA – CS2 exhibited strengths of 3761 PSI at 3 days, 4544 PSI at 7 days, and 5466 PSI at 28 days. IIA – CS3 exhibited strengths of 3828 PSI at 3 days, 4506 PSI at 7 days, and 5668 at 28 days. All three samples exhibited similar strengths at 3 days and 7 days. Both colloidal silica samples appear to have considerable strength over the control at 28 days. Comparison of the control to the CS enhanced samples indicates that the strength gain attributed to CS. The results are shown in Figure 8.

Figure 8 - Strength Activity Index of Type I/II cement with CS

ASTM C191 Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle

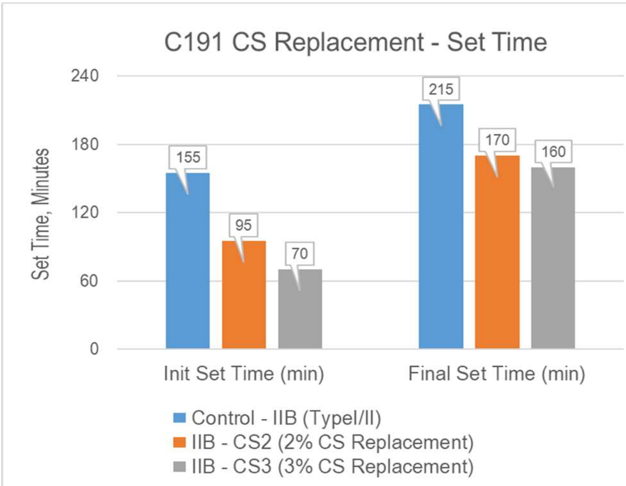

Figure 9 - C191 CS Replacement Set Times at 2% and 3%

The initial set for Control IIB occurred at 155 minutes and the final set at 215 minutes. The PCC technician recorded an initial set time of 95 minutes and a final set time of 170 for IIB-CS2, the 2% CS replacement sample. The technician recorded an initial set time of 70 minutes and a final set time of 160 for IIB-CS2, the 3% CS replacement sample. IIB-CS2 and IIB-CS3 initially set 60 and 85 minutes, respectively, faster than Control IIB. The final set times for IIB-CS2 and IIB-CS3 were 45 and 55 minutes faster than Control IIB. Set time results are shown in Figure 9.

Cost Analysis

Concrete used in 2020 NDOT pavements costs approximately \$125/ yd^3, and includes the cement, aggregate, and any admixtures. According to Nouryon in the spring of 2020, Levasil CB25A cost approximately \$1.25/ lb., or \$12.50/ gallon in a bulk tanker and is shipped on a mass basis. This cost estimate roughly equates to \$12.50/ gallon. As shown in the example below, a 3% CS replacement of F-ash would require 5.6 gallons per cubic yard, costing approximately \$70/ yd^3. Adding CS to a mix design at a 3% replacement level has a negligible effect on the cost of concrete and will result in a cost increase to \$195/ yd^3. Calculations are shown below.

While the powder cementitious material will be reduced, the cost of utilizing colloidal silica will still result in a more expensive mix design, financially preventing NDOT from incorporating CS into regular mix designs. Colloidal silica can be used as a product to remediate cements that do not meet NDOT QA requirements for F-ash content if the PCC engineer is concerned about the cement performance.

<u>Cost of Cubic Yard (CY) with 3% Colloidal Silica Replacement</u>

Gallon Colloid/ yd^3 = *Mass CS/ (Lbs. CS/ Gallon Colloid) = (16.9 lbs. /yd^3 Colloidal Silica) / (3.0 lbs. CS /gallon colloid)*
= 5.6 Gallons Colloid/ yd^3
CB25A Cost = *Gallon Colloid/yd^3 * $Cost_{CB25A}$ = (5.6 gallons colloid/ yd^3) * (\$12.50 /gallon colloid)*
= \$70.00 / yd^3
Cost of Cement/ yd^3 = *(\$150/ ton) * (1 ton/ 2,000 lbs.) * (564 lbs. /yd3)*
= \$42/ yd^3
Cost of 3% Cement Reduction/ yd^3 = *(\$150/ ton) * (1 ton/ 2,000 lbs.) * (547 lbs. /yd3)*
= \$41/ yd^3
Cement Savings = *(Cost of Cement/ yd^3) – (Cost of 3% Cement Reduction/ yd^3) = \$42 - \$41*
= \$1.00/ yd^3
Cost of Cubic Yard with 3% Colloidal Silica Replacement = *CY Concrete + CB25A CS Cost – Cement Savings = \$125 + \$71 - \$1*
= \$195/ yd^3

Conclusions and Recommendations

Colloidal silica shows promise in its ability to mitigate against ASR when used as a replacement of F-ash at both 2% and 3% levels. The 3% replacement of F-ash in a 78% Type I/II and 22% F-ash blended cement showed the greatest reduction in C1567 expansion. This indicates that CS is a viable option for replacing F-ash to mitigate ASR. Furthermore, the CaO/SiO_2 ratio of a cement can be determined through chemical analysis and colloidal silica blends can be designed at specific ratio levels known to NDOT PCC engineers to provide adequate ASR mitigation.

Strength Activity Index and Set Time testing with Type IP cement showed that cements with CS were comparable to the Type IP control used in the study. No significant advantage for compressive strength or set time was gained by adding CS at the 1% level.

Strength Activity Index and Set Time testing with Type I/II CS at 2% and 3% replacement with cement showed a strength gain increase over the control of nearly 1000 PSI at 28 days, and reduced set time by 45 to 55 minutes from the control. This may provide some value to projects that need to open quickly.

Despite CS's successful test results, the cost of CS is too high to use in normal NDOT mix designs and construction activities. Utilizing CS at the 3% level results in about a 66% cost increase for a cubic yard of concrete from \$125/ yd^3 to \$195/ yd^3. Based on cost estimates provided in the Spring of 2020, 30%-wt. colloidal silica will increase the cost of concrete by \$23 for every 1% replacement of Class F fly-ash.

The NDOT PCC engineer recommends that CS can be a tool for concrete or ready-mix suppliers to remediate F-ash deficient cements, when CS will be more cost effective than transporting a IP cement that fails NDOT specifications and/or if it will prevent the IP cement from being removed from Nebraska's Approved Products List.

Future Consideration

Future research will prepare the Department to remediate cements not meeting Quality Assurance standards by providing the PCC engineer with additional tools to improve the long-term performance of concrete structures.

If the use of CS becomes feasible in the future, the PCC engineer proposes testing using colloidal silica as a 3% replacement of F-ash in a mix design. Future testing should include testing CS concretes for all mechanical and durability properties such as: compressive strength, modulus of elasticity, flexure strength, freeze-thaw, NDOT Wet & Dry, and shrinkage. Researches should also investigate the ability to use colloidal silica in a mix design that conforms to the Department specifications.

Water requirements when using CS requires further investigation to better understand how colloidal silica affects workability.

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Appendix A: Calculations for Field Use

Calculation for Colloidal Silica Replacement (SCM)

Colloidal silica can be utilized in Nebraska mix designs as an option for mitigating ASR in concretes with a low F-ash content. Colloidal silica replaces an equivalent percentage of the cementitious powders mass and is considered as an SCM for the purposes of batching calculations.

Calculations for replacement are based on the mass percentage of powder cementitious materials in a mix design. Colloidal silica replacement reduces the amount of powder cement in a batch of concrete. The colloidal silica percent-replacement is based on the silica nano-particle mass in a dose of colloidal silica. The silica mass replaces mass of powders in mix design, and the prime water mass is reduced to offset the mass introduced by the colloid.

The water requirement in the mix design will change. During C109 and C191 testing, the water requirement adjusted until the appropriate measures were made. For both addition and replacement calculations, reducing the water requirements by 3.0 – 3.5% provided workable mixes. Further research is necessary to determine if water requirements can be calculated empirically or if water requirements must be adjusted in the field to achieve desired workability.

In a replacement scenario, the desired mix design will take into account the cement provided by the manufacturer. For instance, to achieve a mix design of 564 lbs. cement /yd^3 comprised of 78% Type I/II Portland cement, 19% Class F Fly-ash, and 3% colloidal silica, cement manufacturers will provide a cement that is 80.4% Type I/II and 19.6% Class F-ash of which 547.1 lbs. /yd^3 will be batched in. When the colloidal silica is batched in with the tail water, it will effectively reduce the Portland and F-ash content in the mix to the desired levels. The mix design for this scenario is shown in Table 7. The colloidal silica properties are shown in Table 8.

Table 8 - A mix design where colloidal silica replaces F-ash.

MIX DESIGN	
Total Cementitious – (Type I/II 78% – F-ash 19% – CS 3%)	*564 lbs. /yd^3*
W/C Ratio	*0.41*
Total Water Required	*231.2 lbs. /yd^3 ~ 27.75 gal.*
Colloidal Silica Replacement	*3%*

Table 9 - Colloidal silica properties provided by Nouryon for a 30% concentration colloid.

COLLOIDAL SILICA PROPERTIES From Manufacturer	
Concentration %-wt (CS%)	*30.3%*
Specific Gravity (SG)	*1.208*
Density Water	*1685.5 lbs. /yd^3 ~ 202 gallons*

Calculations

Cement and Colloidal Silica Mass Requirements per Cubic Yard

Mass CS = *Total Cementitious * Colloidal Silica Replacement = (564 lbs. /yd^3) * (3%)*
= 16.9 lbs. /yd^3
Mass Cement Powder* = *Total Cementitious - Mass CS = (564 lbs. /yd^3) – (16.9 lbs. /yd^3)*
= 547.1 lbs. /yd^3

**The composition of cement powder needed to achieve the final mix design is calculated based on the mix design cementitious mass.*

Mass Type I/II = *Total Cementitious * Type I/II Fraction = (564 lbs. /yd^3) * (78%)*
= 439.9 lbs. /yd^3
Mass F-ash = *Total Cementitious * Type I/II Fraction = (564 lbs. /yd^3) * (19%)*
= 107.2 lbs. /yd^3

Composition of Cement Provided by Manufacturer

Type I/II = *Mass Type I/II ÷ Mass Cement Powder* = (439.9 lbs. /yd^3) ÷ (547.1 lbs. /yd^3) * 100%*
= 80.4%
F-ash = *Mass F-ash ÷ Mass Cement Powder* = (107.2 lbs. /yd^3) ÷ (547.1 lbs. /yd^3) * 100%*
= 19.6%

Colloidal Silica Dose per Cubic Yard

Density colloid = *SG * Density H_2O = (1.208) * (8.34 lbs/gal)]*
= 10.1 lbs. /gallon
Lbs. CS/Gallon Colloid = *Density Colloid * Concentration CS%-wt. = (10.1 lbs. /gallon) * (30%-wt.)*
= 3.0 lbs. CS /gallon colloid
Gallon Colloid/yd^3 = *Mass CS/ (Lbs. CS/ Gallon Colloid) = (16.9 lbs. /yd^3 Colloidal Silica) / (3.0 lbs. CS /gallon colloid)*
= 5.6 Gallons Colloid/ yd^3

Water Requirements Using CS as a Replacement (Assuming a 3% Prime Water Reduction)

Total Design Water Mass Required *= Total Cementitious * w/c ratio = (564 lbs. /yd^3) * (0.42)*
= 231.2 lbs. /yd^3
Total Water Volume Required *= Total Water Mass Required ÷ Density Water = (236.9 lbs. /yd^3) ÷ (8.34 lbs. /gallon)*
= 27.7 gallons /yd^3
Prime Water Volume /yd^3 *= Total Water Volume Req. * 97%*
= 27.7 gallons /yd^3
Colloid Water Mass *= Density Colloid * (1- Concentration CS% wt.) = (10.1 lbs. / gallon) * (1-30%-wt.)]*
= 7.1 lbs. /gallon Colloid
Colloid Water Volume Fraction *= Colloid Water Mass/ Density Water = (7.1 lbs. /gallon Colloid) ÷ (8.34 lbs. /gallon H_2O)*
= 0.85 gallons H_2O /gallon Colloid
Colloid Water Volume /yd^3 *= Gallon Colloid /yd^3 * Colloid Water Volume = (5.6 Gallons Colloid /yd^3) * (0.85 gal. H_2O /gal Colloid)*
= 4.7 gallons H_2O /yd^3